TFAWS Active Thermal Paper Session

Loop Heat Pipe Wick Fabrication via Additive Manufacturing

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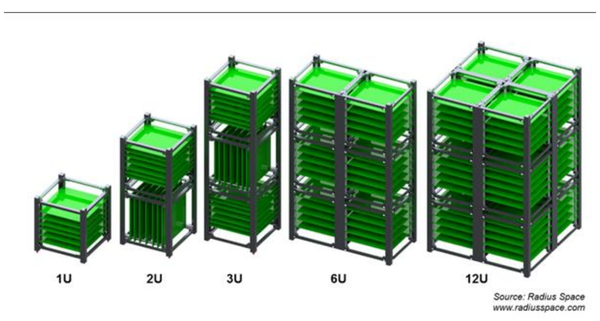
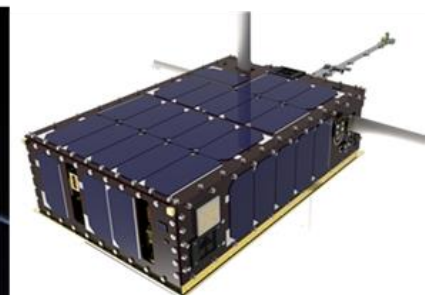
Background

- CubeSats and SmallSats are becoming increasingly popular due to their lower development times and costs
  - NASA’s Small Spacecraft Technology Program under the Space Technology Mission Directorate has been established to develop technology for CubeSats and other small spacecraft
- Advances and miniaturization of electronics has increased the capabilities of the CubeSat platform
  - Higher power components require a thermal management system



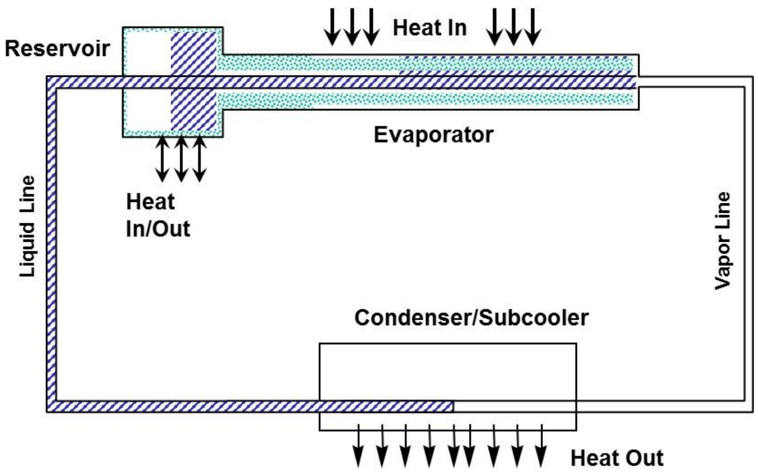


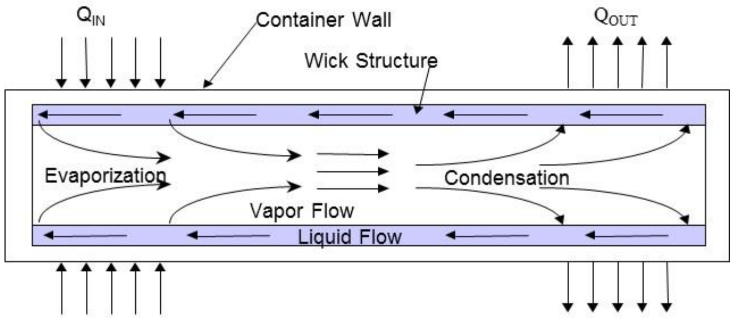
Motivation

- Loop Heat Pipes (LHPs) are a passive and flight tested solution
  - Currently LHPs are very costly to manufacture
    - >$25,000 for standard LHPs, > $100,000 for custom LHPs
    - Will take up a significant fraction of the total CubeSat cost
- By using additive manufacturing the cost of LHP fabrication can be reduced
  - Eliminates machining of the wick
  - Less steps resulting in less labor and shorter fabrication time
    - Currently, primary wicks are tested to confirm performance after each step
- The goal of this work is to develop a low cost loop heat pipe (LHP) through additive manufacturing which can be used on CubeSats to increase the current maximum power levels of onboard instruments

Loop Heat Pipes

- A LHP is a passive two-phase heat transport device that can transport a large heat load with a small temperature difference
  - Totally Passive
  - Transport and condenser tubes are flexible, bendable, and easily routed through complex paths
  - Transports heat over large distances
  - Insensitive to gravity
  - Automatically regulates its operating temperature based on energy balance in the reservoir
  - Reservoir is co-located with the evaporator and hydraulically coupled with a secondary wick
- Compared to a heat pipe
  - Higher powers
  - Longer lengths than a heat pipe
  - Higher adverse elevations
  - More expensive

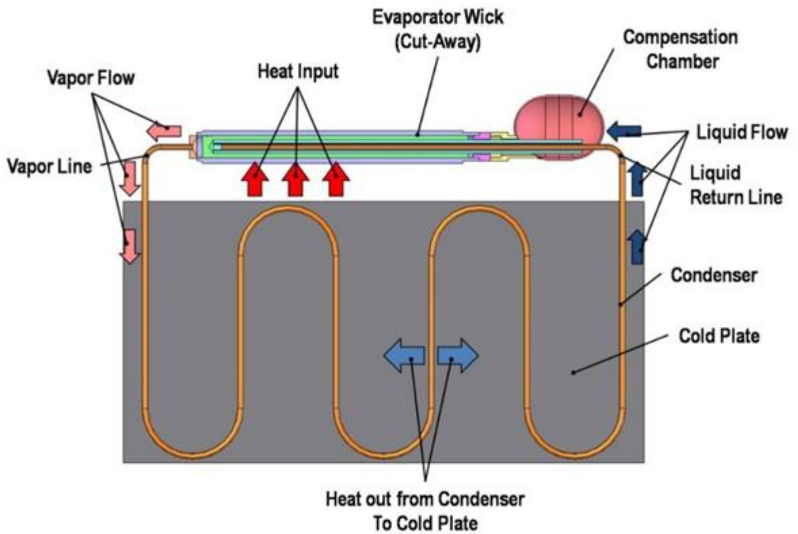


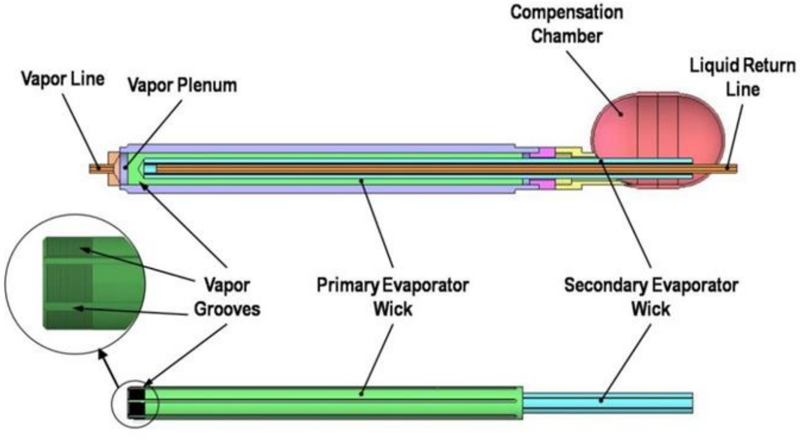


LHP's and CCHP's are baselined for thermal control systems in many spacecraft and terrestrial applications

Loop Heat Pipes

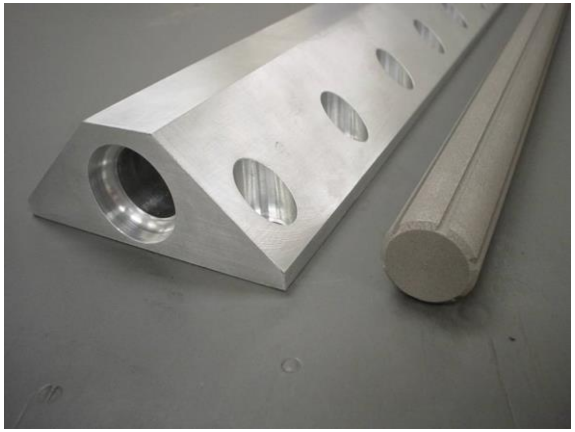
- As heat is applied to the evaporator, liquid is vaporized at the perimeter of the primary wick
- The meniscus formed at the liquid/vapor interface in the evaporator wick develops capillary forces to push the vapor through the vapor line to the condenser
- The vapor is condensed and the liquid is sub-cooled in the condenser
- The cold liquid returns through the liquid line to the reservoir
- The reservoir contains a two-phase mixture of liquid and vapor in thermal equilibrium
  – The reservoir is at a lower temperature and pressure than the vapor side of the primary wick
- Liquid and vapor communication between the reservoir and the primary wick

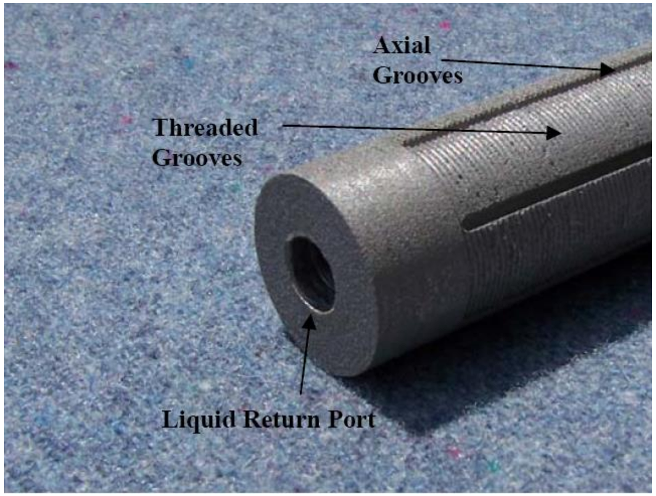




LHP Primary Wick

- Typical LHP wicks are metallic (nickel, stainless steel, monel, titanium) and have a pore size of approximately 1 micron
  - By comparison, the smallest pore size in heat pipe wicks is approximately 50 microns
  - Heat is applied to the concave side of the meniscus unlike in a heat pipe where heat is applied to the convex side
- LHP Wick is sintered, then machined to fit into the LHP Evaporator



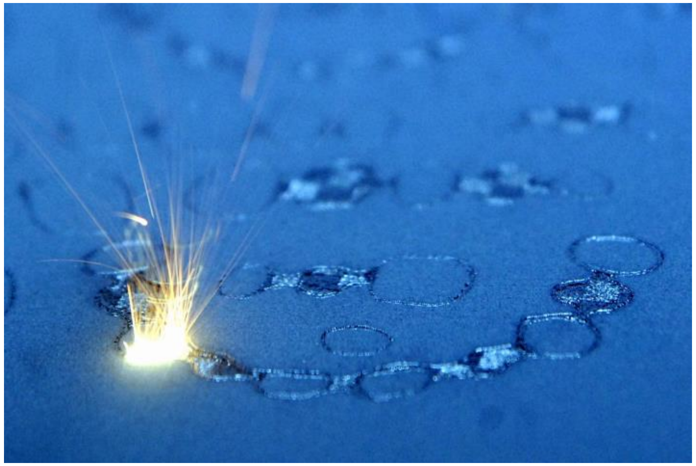


LHP Fabrication

- Current fabrication techniques require testing after each step to ensure compliance with the design specifications
  - Direct Metal Laser Sintering (DMLS) can produce the primary and secondary wicks in a single step reducing the amount of testing required
- Knife-edge seals are the most problematic step in the fabrication process and a common source of long term failure
  - Eliminated by using DMLS
- Machining of sintered powder wicks is required adding to the total cost
  - DMLS eliminates machining of primary and secondary wicks

Direct Metal Laser Sintering

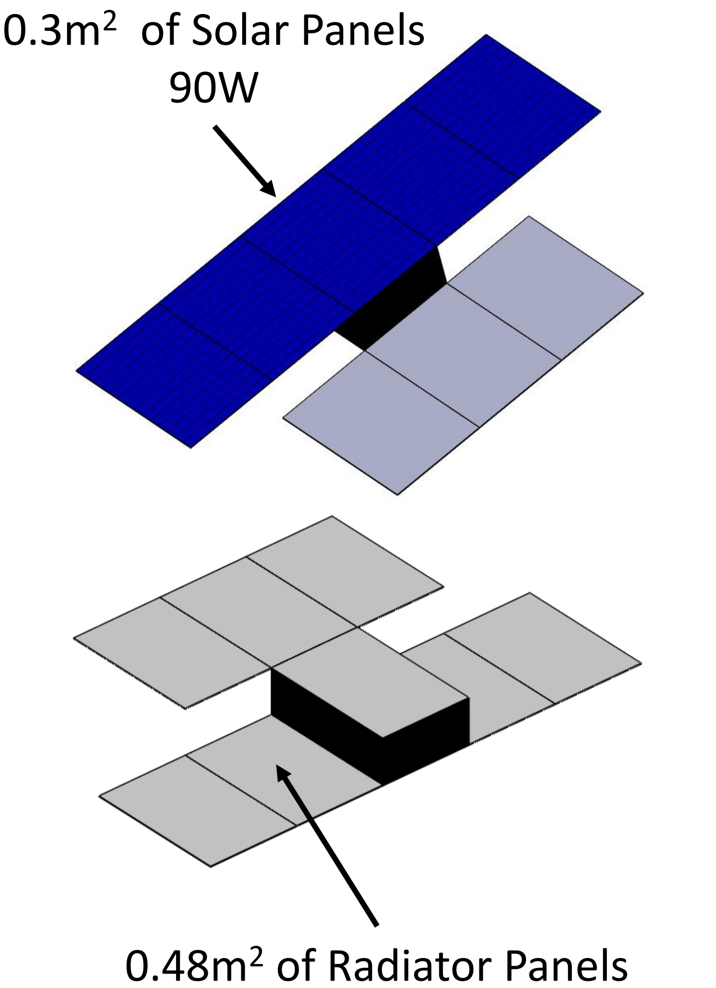
- DMLS is a process by which metal structures are made in a layer-by-layer sintering process that selectively melts powdered metal
  - Assemblies can be created with a specified porosity up to 100% dense and achieving hermetic seals between regions
  - Intricate structures can be made with features on the order of 10's of microns (limited by powder particle size and laser resolution). Limits on minimum pore sizes (porosity) are yet to be determined
  - Structures and features can be made internal to an enclosure
  - Continuous thermal pathway through structures and features, free of thermal interface resistances that would be evident if traditional bonding techniques were used to join parts
- More materials are becoming availab
  - Stainless Steel (17-4, 15-5, 316L alloys)
  - Ti64 Titanium (Grade 5)
  - Aluminum (AlSi10Mg)
  - Inconel 718
  - Cobalt Chrome (MP1)
  - Maraging Steel (MS1 Tooling Steel)



Design Specifications

- 6U Design Requirements
  - 90W maximum heat input
  - Heat source footprint: 15 cm x 3 cm (heat flux = 2 W/cm^2)
  - 0.47 m^2 radiator area (~8 20cmx30cm faces)
  - Heat transport length about 3.2m
- Target cost of the complete system is <$5,000
  - Includes 3D printed evaporator, evaporator saddle, deployable radiator, tubing, and compensation chamber

CubeSat Size	6U
Peak Solar Power (W)	90
Evaporator Temp (K)	273
Radiator Panel Temp (K)	253
Sink Temp (K)	100
Emissivity	0.85
Radiator Area (m^2)	0.467
Transport Length (m)	3.2



LHP Pressure Drop

- Total pressure drop in LHP

$$\Delta P_{total} = \Delta P_{groove} + \Delta P_{vap} + \Delta P_{liq} + \Delta P_{cond} + \Delta P_{wick} + \Delta P_{grav}$$

- Capillary pressure provided by primary wick

$$\Delta P_{cap} = \frac{2\sigma \cos\theta}{R_p}$$

$\sigma = \text{surface tension}$ $\theta = \text{contact angle}$ $R_p = \text{pore radius}$

- Pressure drop through wick (Darcy's Law)

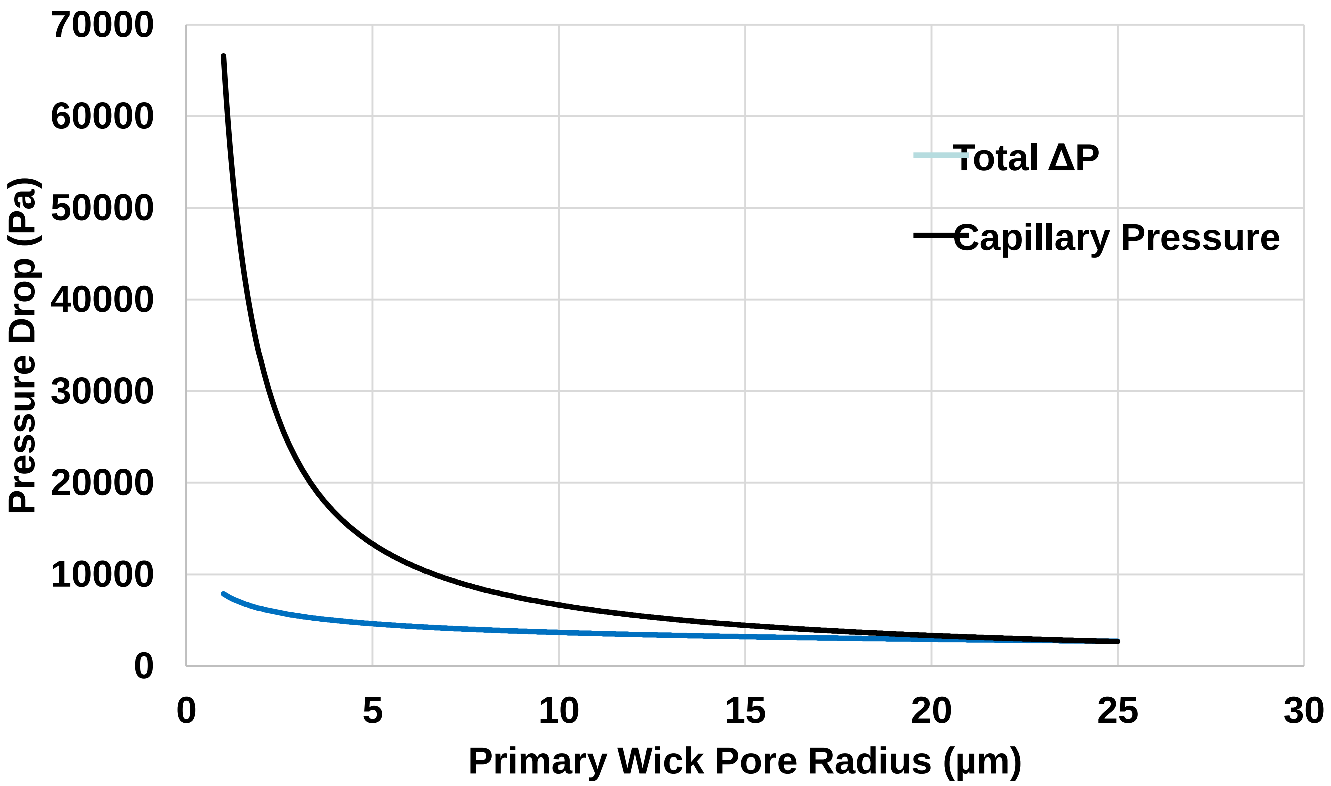
$$Q = \frac{-KA\Delta P}{\mu L}$$

- Decreasing the pore radius results in more capillary pressure to overcome pressure losses

$\text{Q} = \text{volumetric flow rate}$ $\text{A} = \text{cross } sectional\ area$ $\mu = \text{viscosity}$ $L = \text{flow length}$

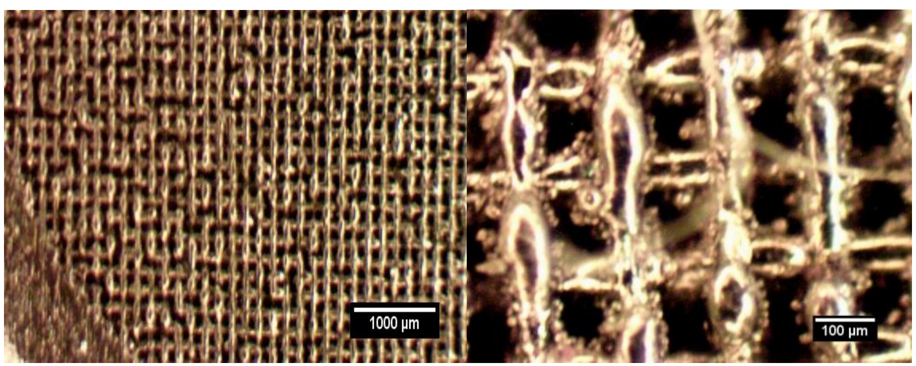
Prototype Pressure Drop

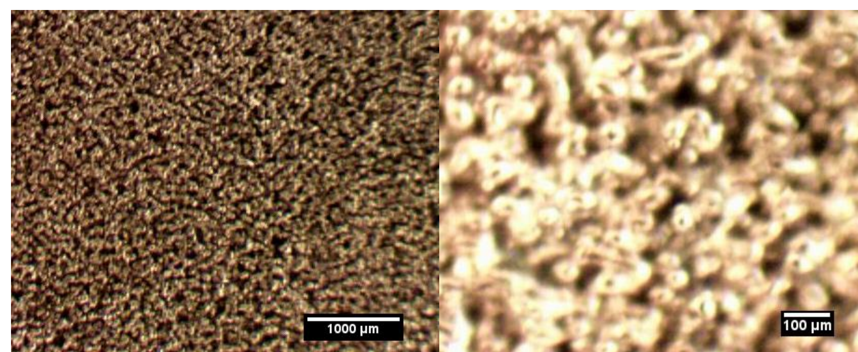
- Pressure drop calculated for LHP transporting 90W across a distance of 3.2m
- Maximum pore radius is 21μm
  - Goal is to minimize pore radius to maximize pressure drop margin



3D Printing Porous Parts

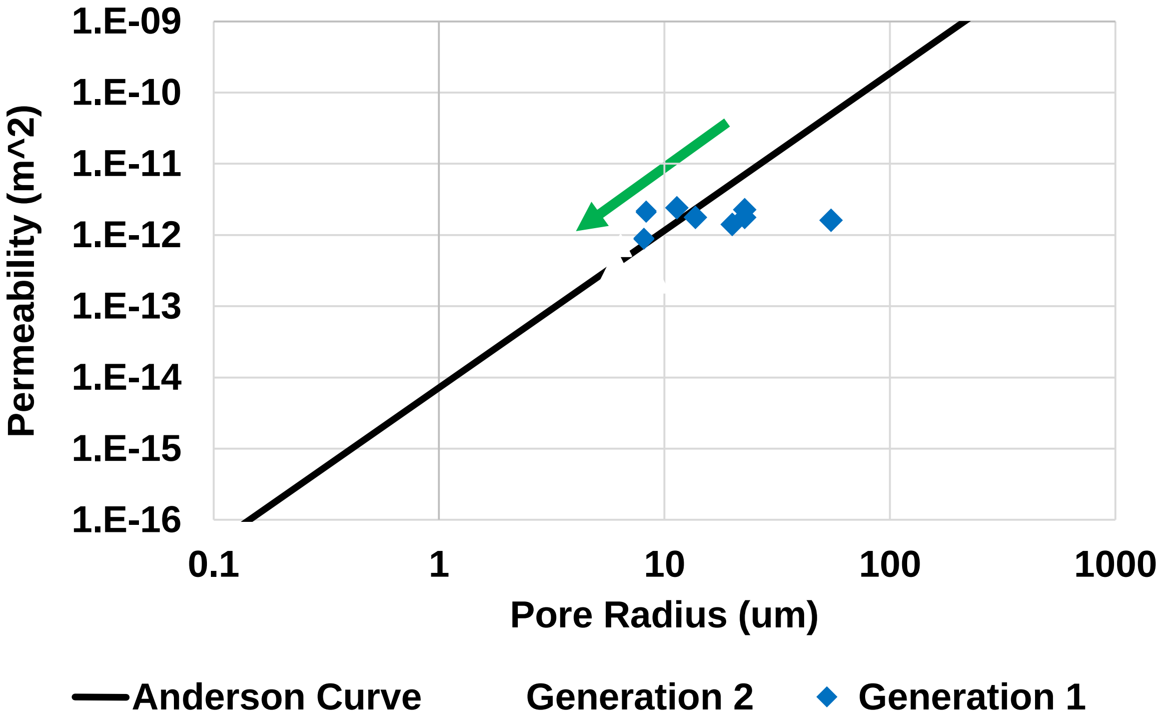
- Multiple approaches can be taken to achieve porous parts using DMLS
- A crosshatch pattern can be used with pore size determined by laser path spacing
  - Minimum pore size limited by laser diameter and accuracy
- Laser power and speed can be reduced to sinter metal particles together without fully melting
  - Replicates traditional wicks produced through sintering in a furnace





3D Printed Wick Samples

- New wick fabrication method has reduced minimum achievable pore radius from 10µm to 6µm
  - Increases capillary pumping power from 6,700 Pa to 11,000 Pa

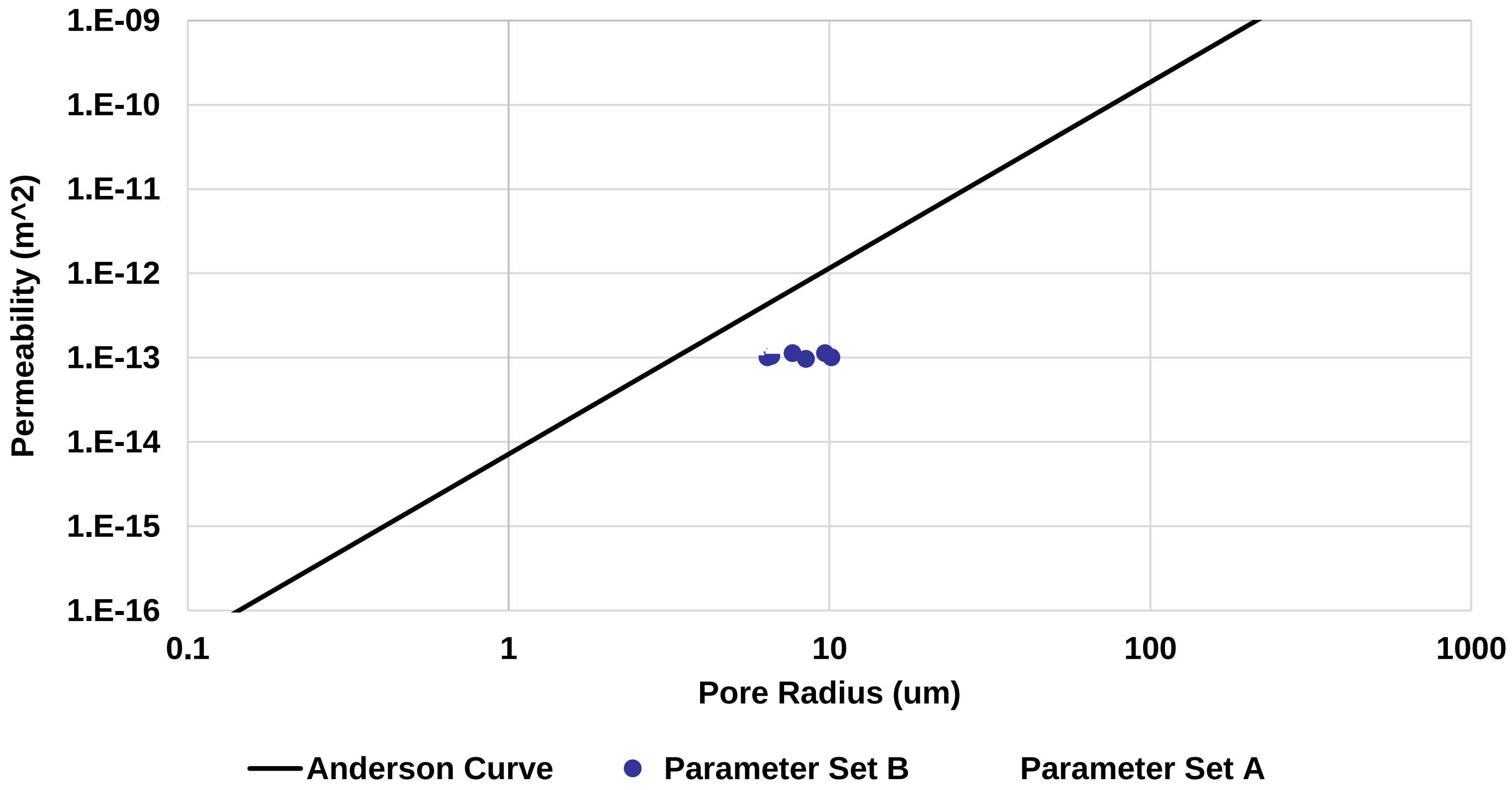


Generation 2

Generation 1

Repeatability Study

- Six parts were printed using the two most promising DMLS parameter sets
  - Samples made using parameter set A form a tight grouping while the pore radius of parameter set B samples ranges from 6 to 10μm
  - Parameter set A was used to fabricate the prototype primary wick

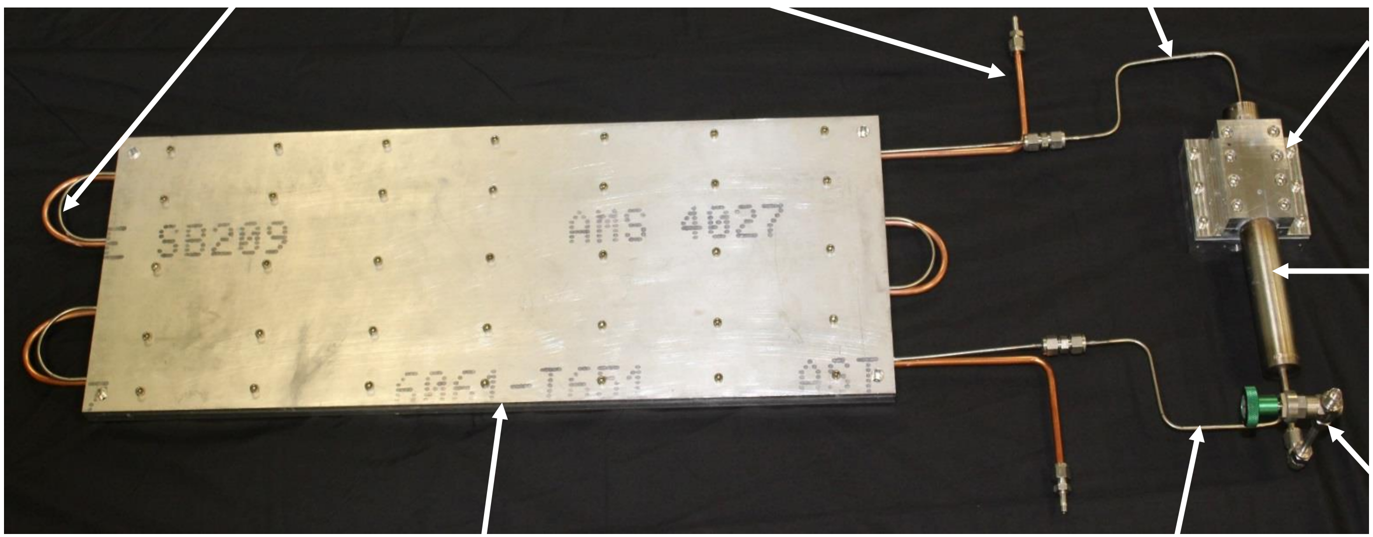


3D Printed Primary Wick

- Primary wicks printed and envelope machined smooth
  - 1” diameter, 4” long
- Helium leak checked
  - Leak rate is less than $5x10^{-9}$ std cm/s
  - 3-D printed envelope is hermetic
- Pore radius measured to be 44µm
  - Much larger pores than expected
  - Recently discovered that incorrect material was used
    - Expect that primary wick can be printed with 6µm pore radius

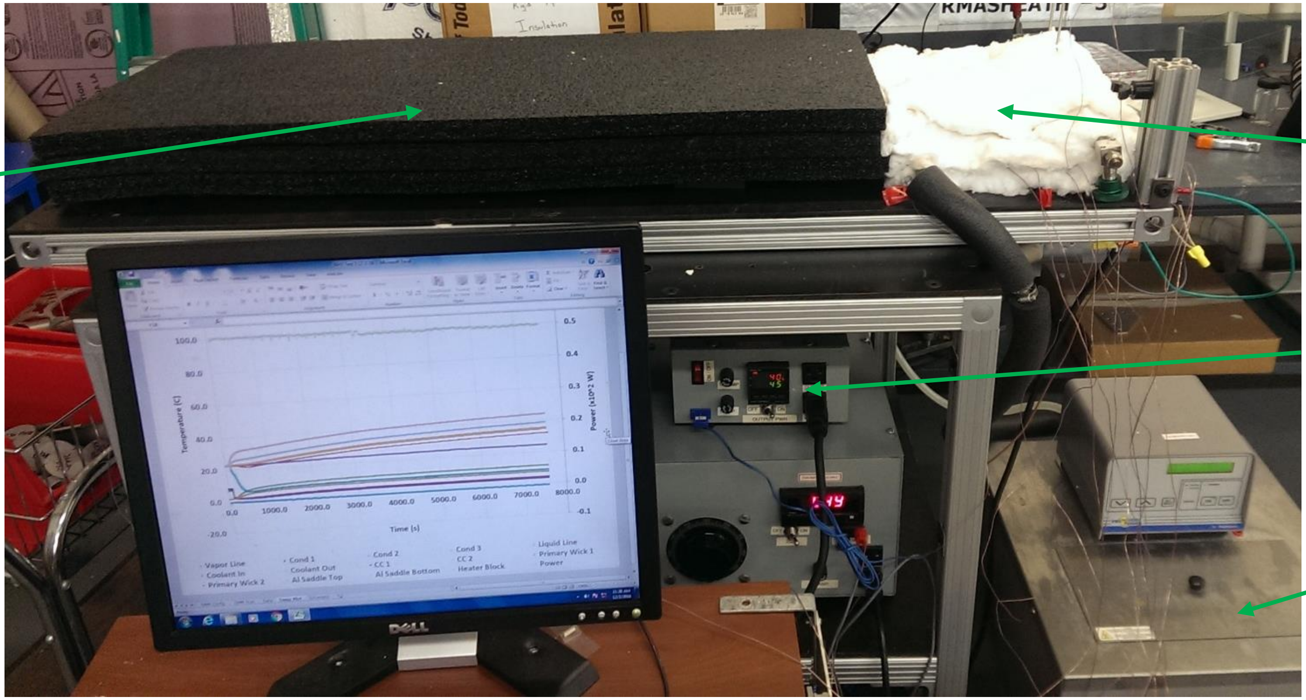
LHP Fabrication

- Compensation chamber and vapor line welded onto primary wick
- All parts in contact with ammonia are 316SS
- Swagelok connection to condenser
- Charged with 35g ammonia

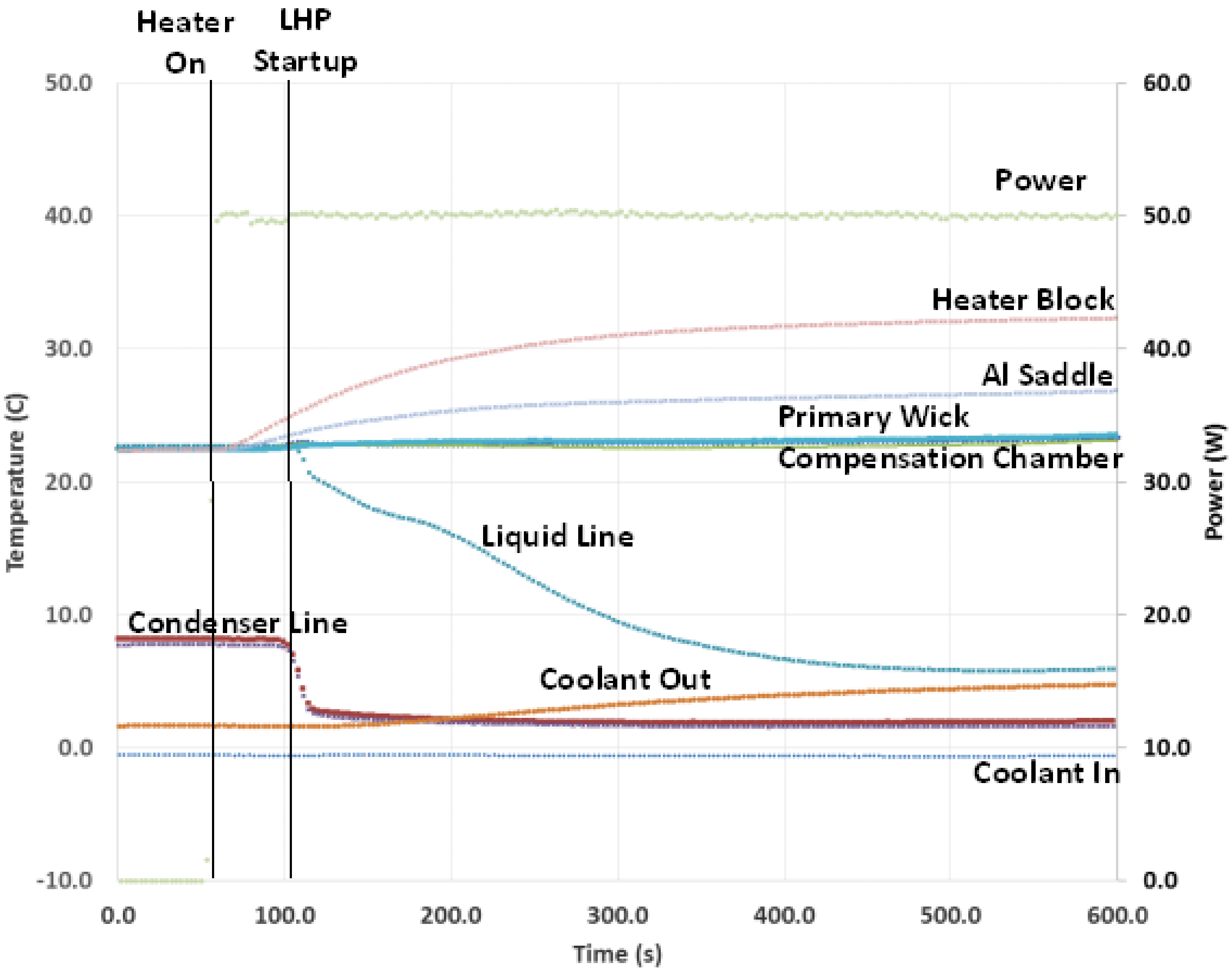


LHP Testing

- LHP well insulated to prevent heat leak
- Chiller set for coolant temperature of -5C
- Over temp controller set to shut off power to cartridge heaters at 45C for safety
- Expected max power of 55W due to 44μm primary wick pore radius



LHP Testing


Heater On
LHP Startup
Power
Heater Block
Al Saddle
Primary Wick
Compensation Chamber
Liquid Line
Condenser Line
Coolant Out
Coolant In
Temperature (C)
Power (W)
Time (s)
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.0
100.0
200.0
300.0
400.0
500.0
600.0

Future Work

- A more in depth pore radius and permeability study will be completed
  - Samples of varying sizes will be 3D printed to determine cause of increased pore radius in primary wick
- Accelerated life testing will be completed to verify material compatibility and long term structural integrity
- The ability of using DMLS to create graded wicks will be investigated
  - Fine wick around the vapor grooves with coarser wick closer to center to reduce pressure drop without lowering capillary pressure
- 3D printed LHP design will be optimized for improved thermal performance and reduced volume
- A flight ready LHP will be built and tested

Conclusions

- Small scale pore radius and permeability testing demonstrated that DMLS can be used to create wicks with pore radii of 6μm
  - A 6μm primary wick will provide enough capillary pressure for the power levels and radiator sizes expected for CubeSat and SmallSat applications
- DMLS offers a significant reduction in the cost of primary wick fabrication
- 3D printed primary wicks can be designed for direct welding to the compensation chamber eliminating the knife edge seal
- 3D printed parts can provide a hermetic seal
- Further development is required to match the performance of current LHP technologies

Acknowledgments

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